TECTONIC SETTING OF LATE ARCHEAN BIMODAL VOLCANISM IN THE MICHIPICOTEN (WAWA) GREENSTONE BELT, ONTARIO

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ABSTRACT

The tectono-stratigraphic relationships, depositional environments, rock associations and major (129 samples) and trace (35 samples) element compositions of the late Archean (2743 - 2695 Ma) bimodal basalt-rhyolite volcanic rocks of the Michipicoten (Wawa) greenstone belt, Ontario are compatible with an origin along a convergent plate margin that varied laterally from an immature island-arc built on oceanic crust to a more mature arc underlain by continental crust, similar to the Cenozoic Taupo-Kermadec-Tonga volcanic zone. Michipicoten basaltic rocks, most of which are similar compositionally to modern oceanic island-arc tholeiites, are interpreted to have formed along the largely submerged island-arc. Voluminous Michipicoten rhyolitic pyroclastic rocks are believed to have been erupted subaerially from the continental-arc, and in large part, deposited subaqueously on the adjacent oceanic island-arc. The compositional similarity between the lower (2743 Ma) and upper (2695 Ma) volcanic sequences of the belt suggests that this island- and continental-arc configuration existed for at least 50 Ma. The Michipicoten belt may be a remnant of a larger, laterally heterogeneous volcanic terrane that also included the Abitibi greenstone belt.

1. Introduction

Two important observations have been made in recent years that bear directly on the tectonic setting of late Archean (2760-2700 Ma) greenstone belts of the Canadian Shield. First, volcanic rocks that comprise many of the belts are largely bimodal in composition, with voluminous rhyolites that in many cases are equal to associated basalts in abundance [1]. Second, sedimentologic [2] and isotopic [3] data indicate that pre-2760 Ma old sialic crust existed beneath, or along the flanks of, many greenstone belt sequences, at least for the time during which some of their volcanic, plutonic and sedimentary components were being formed.

These observations have led many workers to reject oceanic island-arc [4] and continental-arc [5] models for the origin of the belts, in favor of intracontinental rift models [6,7], based on the well-known [8] Cenozoic association of voluminous bimodal basalt-rhyolite volcanism and extensional tectonism within continental terranes. In this paper, the tectono-stratigraphic relationships, depositional environments, rock associations and chemical characteristics of the particularly well-exposed late Archean bimodal volcanic rocks of the Michipicoten (Wawa) greenstone belt, Ontario (figure 1) are shown to be analogous to Cenozoic volcanic rocks found at convergent plate margins. Thus, the Michipicoten belt more likely originated at a convergent plate margin rather than in an intracontinental rift.

2. Geologic relationships

The Michipicoten greenstone belt is an Archean volcanic-sedimentary sequence that has undergone a complicated history of folding, faulting, granitoid intrusion and greenschist facies metamorphism. The geology of the belt has been described by several workers [9-11], but the mapping of Attoh [12,13] forms the basis of the discussion presented here (figure 2, 3). Studemeister [14] has studied the greenschist facies mineralogy of the volcanic and plutonic rocks. Turek et al. [15] have dated selected felsic volcanic rock units by the U-Pb zircon method, delineating the ages of volcanism within the belt and identifying granitoid units older than the greenstones in the surrounding gneiss terrane.

Three time-equivalent stratigraphic sequences of volcanism (figure 4), each including both mafic and felsic rocks, have been recognized in the Michipicoten belt. The lower volcanic sequence is the most well-preserved and consists of a largely mafic unit (MV1) locally overlain conformably by a thick (less than 300m up to about 2000m), mainly felsic (rhyolitic) volcanic succession (FV1), which was emplaced about 2743 Ma ago [15]. In the Michipicoten Harbour area (figure 2), an undated basal felsic flow unit is structurally discontinuous with the mafic sequence. Along the northern margin of the belt, epiclastic sediments are deposited on, and probably derived from, apparently older granitoid rocks (column D, figure 4). The sediments are overlain by felsic volcanics (and iron formation) that may be time-correlative with the Michipicoten Harbour felsic lava flows.

The middle volcanic sequence is separated from the lower sequence by chert-siderite-pyrite-magnetite-bearing (Algoma-type) banded iron formation [16]. The tectono-stratigraphic relationship between the mafic and felsic volcanic rocks of the middle sequence is not well-understood, however, the felsic rocks are believed to have an age of about 2717 Ma [15]. A pebble- to boulder-size conglomerate, the Dore Formation, and time-equivalent greywacke, shale, siltstone and mudstone units unconformably overlie the middle volcanic sequence. In the Michipicoten Harbour sequence, the pre-Dore volcanics show evidence of erosion and folding prior to Dore deposition.

In the Josephine Lake-Mildred Lake area of the belt (figure 3), mafic flows of the upper volcanic sequence conformably overlie the Dore sedimentary rocks, and a thick (up to 2000m) breccia unit unconformably overlies the mafic flows. Upper sequence felsic volcanic rocks such as those at Catfish Lake, which have been dated at 2695 Ma [15], locally cap the sequence (column B, figure 4).

A distinctive characteristic of the Michipicoten belt is the excellent exposure of thick, well-preserved sequences (up to 2000m for unit FV1, up to 500m for unit FV3) of felsic volcanic rocks. Many other greenstone belts of the Canadian Shield have had substantial portions of their felsic volcanic rocks removed by erosion [17].

3. Depositional environments

The physical characteristics of the volcanic, volcaniclastic and sedimentary rock units of the Michipicoten belt reflect subaerial, shallow subaqueous and locally deeper water depositional environments. Most of the mafic volcanics are pillowed lava flows and hyaloclastites erupted under subaqueous conditions, but at least local subaerial mafic volcanism is suggested by the high amygdule content of some non-pillowed flows [18].

Several types of felsic volcanic rocks also have been recognized in the belt including subaerial lava flows and domes, shallow water accretionary lapilli-bearing hyalotuffs, and massive to bedded pyroclastic flows, which volumetrically dominate the volcanic sequence [12,18]. The massive pyroclastic flows are similar to modern non-welded subaerial ash-flow tuffs, whereas the bedded pyroclastics are interpreted to be eruption column collapse deposits that were carried down the flanks of subaerially emergent tuff cones, and onto the ocean floor, by mass flow and turbidity currents. Thin, well-bedded ash-size deposits comprise the upper layers of both the proximal and distal parts of the bedded pyroclastic flows and are believed to have been deposited from turbulent suspensions. The proximal ash beds are similar to the "proximal bedded pyroclastic-flow (PBPF) deposits" described recently from Mount St. Helens [19].

The thick, poorly sorted polymictic breccia unit that comprises a large part of the upper volcanic sequence has a similarly complex depositional history. Attoh [13] interprets the unit to be a subaerial debris flow with subaqueously deposited distal components interbedded with pillowed mafic volcanic rocks. The breccia is composed of rhyodacitic to rhyolitic block-size fragments in a felsic granular matrix, suggesting a largely felsic source terrane.

The sedimentary rocks of the Michipicoten belt include two facies associations [20]. A marine association includes conglomerate, greywacke and mudstone that probably were deposited on submarine fans or volcano flanks by turbidity currents. A non-marine assemblage of cross-bedded sandstone and conglomerate is interpreted to have been deposited in braided fluvial and alluvial fan environments. Felsic volcanic sources were dominant for both sedimentary associations.

4. Compositional data

Whole rock major element analyses were made for 91 samples from unit MV1 and 27 samples from unit FV1 of the Michipicoten belt. In addition, 17 samples from unit MV1 and 14 samples from unit FV1 that show the least petrographic (quartz or calcite veins not present) and chemical (H_2O + CO_2 usually < 3.0 wt.%, otherwise < 4.0 wt.%) effects of alteration were analysed for trace elements.[1] Representative analyses are presented in Table 1.

The chemical data indicate that the lower volcanic sequence is bimodal in composition (figure 5), with basalts and rhyolites dominant volumetrically. Dacites (62 - 70 wt.% SiO_2) are less abundant and andesites (57 - 62 wt.% SiO_2) are rare. Individual samples of basalt and rhyolite, within units MV1 and FV1, respectively, have similar major and trace element compositions; this supports the tectono-stratigraphic correlation presented in figure 4.

In detail, unit MV1 is composed of basalts and basaltic andesites (49.4 - 56.4 wt.% SiO_2), although dacites (65.2 - 66.2 wt.% SiO_2) and relatively high-silica (74.7 - 78.5 wt.%) rhyolites are present in minor amounts. Two types of basaltic rocks are recognized (figure 6): enriched ($[La/Sm]_n$ = 1.9 - 2.6, Th = 2.0 - 3.0 ppm, Ta = 0.59 - 0.95 ppm, Sr = 310 - 520 ppm, Sc = 20.8 - 37.9 ppm, Co = 19.3 - 39.1 ppm) and depleted ($[La/Sm]_n$ = 0.55 - 1.07, Th = 0.16 - 0.71 ppm, Ta = 0.13 - 0.30 ppm, Sr < 250 ppm, Sc = 39.4 - 45. ppm, Co = 42.6 - 59.9 ppm). Both basalt types exhibit relatively low Mg#'s (100Mg/{Mg + total Fe} ranging from 57.4 to 65.4 for enriched basalts, and between 36.9 and 59.3 for depleted basalts), suggesting significant differentiation following extraction from their mantle source regions, or

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[1] A complete list of analyses may be obtained from the authors. Compositional data described in the text are normalized volatile-free.

derivation from a mantle atypically rich in iron. MV1 depleted basalts are much more widespread and voluminous than the comparatively rare MV1 enriched basalts; the latter have been identified only at the bottom of the mafic flow sequence exposed in Michipicoten Harbour, overlying the thick basal felsic flow unit (column A, figure 4).

The dacites of unit MV1 are interbedded with the depleted basalts and exhibit the distinctive HREE-depleted signature (figure 6, $[Tb/Yb]_n = 2.3$, $Yb_n = 3.5 - 4.3$) characteristic of many Archean dacites [22] and some modern dacites formed at convergent plate margins [23]. In contrast, the rhyolitic pyroclastic rocks of unit MV1 occur at an enriched/depleted basalt interface (figure 2) and are characterized by positive HREE slopes and large negative Eu anomalies (analysis #4, Table 1). A thin high-silica rhyolite lava flow is interbedded with depleted basalts in the Andre Lake area (figure 3). The flow is diluted in REE, Hf, Th, U and Zr relative to the MV1 rhyolite pyroclastic unit (analysis #5, Table 1).

Unit FV1 is composed of rhyolites (71.9 - 79.6 wt.% SiO_2) and volumetrically subordinate dacites (62.2 - 68.8 wt.% SiO_2). High- and low-silica rhyolites in the unit have parallel REE patterns characterized by LREE-enrichment, small negative Eu anomalies and rather flat HREE slopes. The dacites of unit FV1, in contrast to the dacites of unit MV1, are HREE-undepleted ($[Tb/Yb]_n = 1.2 - 1.7$, $Tb_n = 6.4 - 9.4$) and more iron-rich. FV1 dacites have REE patterns similar to FV1 rhyolites (figure 6), suggesting a genetic relationship.

Basalts (analysis #6, Table 1) that are similar compositionally to the enriched basalts of unit MV1 comprise a minor volume of unit FV1. FV1 basalts have REE patterns shaped similar to those of the FV1 dacites and rhyolites, but are enriched in Sm, Eu, Tb and Yb abundances. Thus, it is unlikely that the felsic rocks were produced from the basalts by fractional crystallization.

The chemical characteristics of unit FV3 of the Michipicoten belt also have been studied. Major and trace element determinations were made for 4 samples; 11 samples were analysed for major elements only. The unit consists of voluminous rhyolitic rocks interbedded with smaller amounts of dacite and basalt. Representative analyses of low- and high-silica rhyolite from the unit are listed in Table 1. The FV3 rhyolites are compositionally similar to FV1 rhyolites, particularly with respect to trace elements (e.g., both have $[Tb/Yb]_n$ = 1.2 - 1.5), however some high-silica rhyolite samples may be distinguished by very large negative Eu anomalies ($[Sm/Eu]_n$ = 20.2 - 34.7).

5. Discussion

5.1. A Cenozoic analogue

The main geologic features of the Michipicoten greenstone belt -- i.e., older granitoid rocks flanking an interbedded sequence of basalts, clastic sediments and voluminous felsic pyroclastic rocks deposited primarily, but not exclusively, in a subaqueous environment -- also are characteristic of the rock association present at some Cenozoic convergent plate margins, such as the Kamchatkan and Alaska Peninsula volcanic arcs [24], the Japanese Islands arc [25] and the Taupo-Kermadec-Tonga volcanic zone [26] (figure 7). Along the plate margin of the latter example, subduction is occurring beneath both an immature island-arc built on oceanic crust (Kermadec-Tonga Ridge) and a more mature arc underlain by continental crust (Taupo volcanic zone). Volcanism along the oceanic island-arc is mainly basaltic and largely subaqueous, because the arc is almost completely submerged. However, volcanic islands (the Kermadec and Tonga islands) locally breach sea level and have produced subaerial lava flows.

In contrast, volcanism in the Taupo volcanic zone of New Zealand, which is a continental-arc that is presently undergoing extension, is overwhelmingly (>97.4%) rhyolitic in composition [27]. Moreover, the volcanism is explosive and consequently much of the rhyolitic material erupted from the Taupo volcanic zone actually has been deposited off the northeastern flank of the New Zealand continental margin and on the adjacent sea floor [28]. For example, eighty percent of the Taupo pumice has been deposited at sea, more than 220 km from the vent [28].

Interfingered submarine deposits of oceanic island-arc basalt, continental-arc rhyolite and clastic sediment, formed at a convergent plate margin similar to the Taupo-Kermadec-Tonga arc, may provide a modern analogue for the subaqueous basalt, rhyolite and sediment deposits present in the Michipicoten greenstone belt. This analogy suggests that the Michipicoten belt originated along a plate margin that varied laterally from an immature (i.e., basaltic) island-arc built largely on oceanic crust to a more mature arc underlain by continental crust.

Subaqueously-deposited Michipicoten basalts formed as lava flows along the submerged island-arc, whereas interbedded felsic rocks originated as pyroclastic flows that were erupted subaerially from the continental-arc and deposited subaqueously on the adjacent ocean floor. Subaerially-deposited Michipicoten basalts, which are volumetrically minor, formed where the island-arc locally became emergent. Turbidite formation was initiated where volcano flanks and continental margins were loaded unstably.

Proximally-deposited Michipicoten felsic volcanic and sedimentary rocks, which include most of the subaerial to shallow subaqueous deposits, require at least part of the continental-arc to have been present within the margins of the greenstone belt. However, some of the distally-deposited felsic volcanic and sedimentary rocks may have been derived from a continental-arc source situated completely outside the belt margins. The felsic granitoid rocks that occur along the margin of the belt, and are older than the Michipicoten greenstones [15], could be the remnants of either of these types of continental-arcs.

According to this model, the basalt-rhyolite bimodality of the Michipicoten belt simply is a consequence of the paucity of andesitic magma produced along an immature oceanic island-arc such as the Kermadec-Tonga arc, and along a primarily rhyolitic continental-arc such as the Taupo volcanic zone. The broad compositional similarity between the lower (2745 Ma) and upper (2695 Ma) Michipicoten volcanic sequences suggests that this island- and continental-arc configuration existed for at least 50 Ma.

5.2. Compositional comparisons

Several investigators have made compositional comparisons of Archean and Cenozoic volcanic rock associations, in most cases concentrating on basaltic components [29]. The tectonic significance of such comparisons is limited, however, by two reasons -- the possible secular evolution of magma source composition, and the possible non-unique correlation of magma chemical composition with tectonic setting. Thus, similarities between magma compositions of the Michipicoten volcanic sequence and Cenozoic island- and continental-arc sequences may be taken to be consistent with, but not compelling evidence of, a convergent plate margin origin for the Michipicoten belt.

Despite these uncertainties, it is noteworthy that in Cenozoic terranes, voluminous rhyolitic pyroclastic deposits are erupted only on continental (rather than oceanic) crust and seem to exhibit distinctive rock associations and chemical characteristics depending on whether that crust was the site of intracontinental rifting or subduction. In Table 2, the rock associations, dominant silica ranges and some major element characteristics of rhyolite ash-flow tuffs from the Michipicoten belt and six Cenozoic terranes of known tectonic setting are compared. The Cenozoic rhyolites are subdivided into two groups, one formed in intracontinental rifts or above continental "hot spots" that are not related directly to subduction, and the other formed in subduction-related continental intra-arc regions.

At least for the suites listed in Table 2, the rock association exhibited by the Michipicoten rhyolites is more similar to the subduction-related examples than the intracontinental rift- and hot spot-related suites. In addition to voluminous rhyolitic ash-flow tuff, units FV1 and FV3 of the Michipicoten belt include subordinate abundances of rhyolitic lava and dacitic tuff and lava, as well as minor amounts of basalt. A similar rock association is present in the Taupo volcanic zone [36] and the Sierra Madre Occidental of Mexico [38].

In contrast, the abundant, strongly alkaline basaltic rocks of the rift-related Trans-Pecos volcanic province of Texas [31,39] do not have a counterpart in Michipicoten belt. Voluminous subalkaline basalts, similar to those that comprise the Rio Grande rift of New Mexico and the hot spot-related Yellowstone Plateau volcanic field of Wyoming, are present only in units MV1 and MV3 of the Michipicoten belt, and whereas the Michipicoten basalts are dominantly LREE-depleted, the Rio Grande [33,40] and Yellowstone [41] basalts are exclusively LREE-enriched. Furthermore, subalkaline dacitic rocks, which are believed to be related genetically to the rhyolites in the

Michipicoten suite, are absent in the Trans-Pecos [39] and Yellowstone [34] volcanic fields, and are present only as the felsic end member of an andesitic differentiation series in the Rio Grande rift [33].

The compositional characteristics of the Michipicoten rhyolite ash-flow tuffs also are more similar (with the exception of iron concentrations, which are indistinguishable) to the subduction-related suites, particularly the Taupo rhyolites, than the rhyolites that are not related directly to subduction. The broad silica range (69 to 78 wt.%) that characterizes Michipicoten rhyolite compositions is reflected only by the Taupo rhyolites. The Michipicoten rhyolites exhibit a general relationship, shared by all of the subduction-related rhyolites, of relatively high concentrations of alumina plus lime and low total alkalis. The intracontinental rift- and hot spot-related rhyolites possess relatively lower concentrations of alumina plus lime and higher total alkalis. Moreover, the overall absolute and relative minor and trace element abundances of the Michipicoten rhyolites are very similar to subduction-related rhyolite suites (figure 8).

A broad compositional similarity between modern oceanic island-arc tholeiites and LREE-depleted Michipicoten basalts further supports the interpretation that the Michipicoten belt formed at a convergent plate margin. When plotted on the chondrite-normalized minor and trace element diagram of Thompson et al. [42], modern oceanic island-arc tholeiites, of which those from the New Britian island-arc are a typical example (figure 9), exhibit prominent Sr peaks and Nb, Ta and Th troughs. Compositions of the LREE-depleted Michipicoten basalts possess similar characteristics. In contrast, typical N-type mid-ocean ridge basalt [42] displays a minor and trace element abundance pattern that is compositionally distinct from the Michipicoten basalts. LREE-depleted basalts are not associated with modern intracontinental rifts and hot spots [40], except in rare instances, such as the Preshal Mhor basalts of the Isle of Skye [42], which are more similar compositionally to N-type MORB than island-arc tholeiite (figure 9).

When plotted on the elemental abundance diagram of Thompson et al. [42], the volumetrically minor LREE-enriched basalts of the Michipicoten belt do not exhibit the Sr peaks and Th troughs characteristic of modern island-arc tholeiites (figure 10). Most of these basalts are situated directly above the thick basal rhyolite unit exposed in Michipicoten Harbour (column A, figure 4); the others are interbedded with the rhyolites of unit FV1. Bulk or selective contamination of LREE-depleted Michipicoten basalts by this rhyolitic material, which shows Sr troughs and Th and LREE peaks when plotted in figure 10, may have formed the LREE-enriched basalt compositions.

Finally, it is worth considering the tectonic significance of the rhyolite flow interbedded with the depleted basalts -- here interpreted as oceanic island-arc tholeiites -- of the Andre Lake area of the Michipicoten belt. The Andre Lake rhyolite (analysis #5, Table 1) is volumetrically minor compared to the associated mafic rocks and exhibits several noteworthy compositional characteristics: high-silica (>75 wt.%), $Na_2O > K_2O$, low total REE concentration ($Ce_n = 26.0$, $Tb_n = 4.7$) and LREE enrichment.

In the Fiji [46], New Britian [47] and Marianas [48] island-arcs, small volumes of rhyolite with similar compositional characteristics are present (figure 11). They may be appropriate Cenozoic analogues for the Andre Lake rhyolite. Comparing figures 8 and 11, it is noteworthy that high-silica oceanic island-arc rhyolites possess Th troughs on the element diagram of Thompson et al. [42], in contrast to rhyolites formed in continental-arcs and intracontinental rifts. The Andre Lake rhyolite shows such a Th depletion.

5.3. Further considerations

The data presented in this paper suggest that a convergent plate margin model is more appropriate than an intracontinental rift model for at least one of the late Archean bimodal greenstone belts of the Canadian Shield. However, the results also bear on three other topics: the apparent "cyclicity" of Archean greenstone belt volcanism, the general applicability of back-arc basin tectonic models [49] of Archean greenstone belts, and the relationship of the Michipicoten belt to the very large, well-studied Abitibi greenstone belt.

Interbedded mafic and felsic units in Archean greenstone belts often have been regarded to represent vertically repetitive volcanic cycles of sequentially-emplaced mafic and felsic magmas that may be related by magmatic differentiation processes [50]. An alternative view is that the apparent vertical cyclicity of greenstone belt volcanism actually reflects the lateral facies relationships of independently-derived mafic and felsic magmas that were continuously available for eruption [51].

The Michipicoten data favor the latter interpretation, although rather episodic emplacement is suggested for at least the three main felsic units (FV1, FV2 and FV3), based on their inferred explosive eruption mechanisms, relatively homogeneous chemical and physical nature over fairly great thicknesses and intra-unit isotopic U-Pb zircon age clustering [15]. Nonetheless, the Michipicoten mafic lavas and felsic tuffs are interfingered deposits derived independently from oceanic and continental platforms, respectively. The presence of thin felsic tuff beds within the mafic unit at Michipicoten Harbour, and thin beds of enriched basalt within the felsic tuff unit east of Mildred Lake suggests that both mafic and felsic magmas were continuously available for eruption.

It also has been often argued that Archean greenstone belts represent closed back-arc basins, rather than volcanic arcs or intracontinental rifts [52]. The data presented in this paper indicate that this generalization is not valid for the Michipicoten greenstone belt. The characteristics of the Michipicoten volcanic rocks suggest derivation in island- and continental-arc environments and the lower and middle volcanic sequences of the belt were folded before the initiation of upper sequence volcanism, suggesting compressional tectonism during its early volcanic history. Compressional tectonism is compatible with a convergent plate margin hypothesis, but not a back-arc model, which requires extensional tectonism during the early, pre-closure stages of greenstone belt volcanism. The same argument applies against an intracontinental rift model.

The relationship of the Wawa domal gneiss terrane (an amphibolite facies granitoid sequence adjacent to the Michipicoten belt, as shown in figure 12) to the Michipicoten greenstones also is not that predicted by the back-arc basin model. According to such models [49] relatively high-grade granitoid gneiss sequences adjacent to lower-grade greenstone belts represent plutonic components of the island- and continental-arc terrane behind which the back-arc basin formed. The Wawa domal gneiss terrane, in contrast, is believed to be the exposed plutonic roots of the Michipicoten greenstones, not a separate parallelly-evolving arc sequence [54]. These plutonic roots and deeper level crustal rocks beneath them (the granulite facies terrane of the Kapuskasing structural zone) are interpreted to have been uplifted along a presently northwest-dipping deep-crustal thrust fault (cropping out at the surface as the Ivanhoe Lake cataclastic zone) sometime after the major volcanism and plutonism in the region was complete [54].

Isotopic age data from the Wawa domal gneiss terrane suggest that the majority of the granitoids (primarily tonalites) were emplaced during the later stages of, and following, volcanism in the Michipicoten belt [54]. Thickening of the Michipicoten "island-arc" by tonalite underplating is compatible with the convergent plate margin hypothesis presented in this paper.

The Abitibi greenstone belt is located to the east of the Michipicoten belt (figure 12) and it is possible that both belts represent remnants of a large, once laterally continuous volcanic terrane, particularly in light of the interpretation that deep level crustal rocks have been uplifted to the surface between them. Two volcanic zones have been recognized in the Abitibi belt [6,53]. The southern or external zone formed approximately 2710 to 2696 Ma ago, which is broadly contemporaneous with the upper volcanic sequence of the Michipicoten belt. The northern or internal zone includes an episode of explosive felsic volcanism at about 2717 Ma, which is coeval with middle sequence Michipicoten volcanism, and a major period of mafic volcanism that occurred sometime prior to 2719 Ma, which could be equivalent temporally to either middle or lower sequence Michipicoten volcanism.

A comparison between the two Abitibi volcanic zones and the middle volcanic sequence of the Michipicoten belt, for which detailed compositional and stratigraphic data are not available, cannot yet be made. However, it does seem clear that the lower and upper Michipicoten volcanic sequences differ in several respects from both volcanic zones of the Abitibi belt.

In the southern Abitibi zone, there exists a broad mafic-felsic compositional bimodality similar to that described in the Michipicoten sequences. However, the Abitibi mafic compositions include komatiitic plateau volcanics and the felsic units consist of slightly LREE-enriched ($[La/Yb]_n = 1 - 5$) high-silica (>75 wt.%) rhyolite and andesite. In the

Michipicoten belt, komatiitic volcanics have not been identified and felsic volcanic sequences are dominated by more strongly LREE-enriched ($[La/Yb]_n$ = 4 - 22) dacite and low- to high-silica rhyolite.

The northern zone of the Abitibi belt exhibits a continuous mafic to felsic spectrum of volcanic rocks in contrast to the Michipicoten compositional bimodality. Tholeiitic basalt with roughly chondritic REE patterns ($[La/Yb]_n$ = 0.8 - 1.5) forms the base of the volcanic pile and could be analogous to the depleted ($[La/Yb]_n$ = 0.6 - 1.2) basalts of the Michipicoten mafic sequences, but an overlying succession of voluminous calc-alkaline LREE-enriched ($[La/Yb]_n$ = 1 - 8) basaltic to andesitic and dacitic volcanic rocks has no Michipicoten counterpart. The LREE-enriched ($[La/Yb]_n$ = 4 - 23) basaltic and dacitic lavas of Michipicoten units MV1 and MV3 are volumetrically minor and are not associated with andesite.

Similarly, andesitic, dacitic and rhyodacitic pyroclastic rocks near the top of the volcanic pile in the northern Abitibi belt are dominated by more intermediate compositions than the dacitic to high-silica rhyolite pyroclastic sequences of the Michipicoten belt. At the top of both the northern and southern Abitibi volcanic sequences, strongly alkaline lavas are present, whereas similar lavas have not been recognized in the Michipicoten volcanic sequences.

The aforementioned differences do not rule out the hypothesis that the Michipicoten and Abitibi terranes were once part of a large, laterally continuous volcanic belt, but do suggest significant compositional variations were present along the strike length of any such belt. Many Cenozoic volcanic belts, including those formed at convergent plate margins, show extreme compositional variability along strike. For example, active volcanism along the Andean volcanic belt is characterized broadly by a northern zone of basaltic andesite, a central zone of andesite, dacite and rhyolite, and a southern zone of high-alumina basalt, basaltic andesite and andesite [55]. Thus, if the Abitibi belt originated along a convergent plate margin, as several workers [53,56] have suggested, it is possible that the Michipicoten belt was produced along a lateral continuation of the same plate margin.

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TABLE 1

REPRESENTATIVE ANALYSES OF VOLCANIC ROCKS FROM THE MICHIPICOTEN BELT

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
SiO_2	50.80	51.90	62.70	71.70	77.40	51.20	61.10	70.70	75.70	69.40	76.10
TiO_2	1.27	1.72	0.59	0.11	0.05	1.06	0.64	0.32	0.17	0.43	0.04
Al_2O_3	15.90	15.60	14.90	12.00	12.90	15.90	17.20	14.80	12.40	14.10	14.90
Fe_2O_3	2.80	2.80	1.30	0.70	0.20	3.60	2.00	1.40	0.70	1.40	0.30
FeO	9.50	6.00	3.00	0.90	0.30	6.40	3.30	2.00	0.90	2.00	0.10
MnO	0.18	0.17	0.07	0.05	0.26	0.14	0.07	0.05	0.02	0.03	0.08
MgO	5.12	9.04	4.50	2.41	0.26	5.61	2.75	0.96	0.29	1.02	0.08
CaO	7.73	6.15	1.98	2.44	0.13	8.22	3.49	1.99	1.29	1.25	0.16
Na_2O	3.30	3.10	5.20	1.90	3.50	2.40	5.70	4.60	4.20	5.90	3.00
K_2O	0.68	0.30	1.05	2.67	2.43	0.84	1.93	2.04	2.45	2.44	3.92
P_2O_5	0.10	0.25	0.26	0.03	0.02	0.30	0.18	0.07	0.04	0.12	0.03
S	0.02	0.04	0.02	0.04	0.01	0.03	0.05	0.08	0.08	0.04	0.03
CO_2	0.20	0.10	1.90	1.90	0.20	0.20	0.10	0.70	1.20	0.70	0.20
H_2O	2.00	2.10	1.70	2.00	1.10	3.10	1.40	0.80	0.60	0.70	0.30
Total	99.60	99.27	99.17	98.85	98.76	99.00	99.91	100.51	100.04	99.53	99.24
Rb	14.	9.	24.	99.	45.	14.	50.	61.	42.	52.	89.
Sr	250	320	90	140	100	570	480	140	120	170	50
Ba	60	110	980	410	870	380	590	610	960	790	600
Cs	1.16	0.46	2.48	3.10	2.38	2.34	1.36	0.81	0.44	1.84	1.12
Sc	42.8	37.9	7.70	2.34	1.56	24.8	10.28	5.88	4.17	6.26	2.37
Co	44.3	39.1	11.1	0.445	1.09	34.3	13.8	5.81	2.33	7.81	0.49
Ni	110	110				80					
Cr	154.	235.	16.1	2.3	0.7	130.	13.8	11.1	1.8	6.0	0.4
La	3.36	20.3	31.2	45.1	10.2	30.5	24.3	28.5	35.5	35.6	19.7
Ce	9.7	47.5	69.9	91.5	22.9	63.9	51.5	56.4	72.1	70.7	47.4
Sm	2.49	5.8	6.4	7.2	1.78	5.09	4.1	3.72	4.6	4.37	4.88
Eu	0.86	1.68	1.45	0.89	0.458	1.51	1.06	0.68	0.73	0.96	0.242
Tb	0.63	0.95	0.47	1.31	0.221	0.66	0.45	0.51	0.54	0.44	0.67
Yb	2.77	2.91	0.86	6.8	0.68	2.08	1.38	1.73	1.92	1.20	1.90
Lu	0.43	0.45	0.134	1.01	0.094	0.29	0.225	0.279	0.290	0.197	0.273
Hf	2.2	3.4	3.87	7.2	1.98	3.6	4.9	4.8	5.4	4.78	3.55
Ta	0.16	0.95	0.32	1.61	1.34	0.56	0.74	0.74	0.74	0.71	1.65
Th	0.40	2.01	4.72	19.5	2.94	4.11	5.76	9.8	12.1	7.33	13.3
U	0.37	0.7	1.40	4.7	1.06	0.90	1.4	2.7	3.5	1.69	3.1
Zr		160	160	220	50	140	200	150	190	150	80

Major elements (in wt. percent) determined by XRF (except FeO, H_2O, CO_2 and S by rapid chemical methods) at the Geological Survey of Canada, Analytical Chemistry Laboratory, Ottawa. Trace elements (in ppm) analysed by INAA at Washington University, St. Louis. Anayltical uncertainties (2-sigma) are less than 2.2% for TiO_2, Fe_2O_3, MnO, CaO, K_2O and P_2O_5, 2.6% for SiO_2, Al_2O_3 and MgO, 4.2% for FeO and Na_2O, 5% for all trace elements except those listed below, 10% for CO_2, H_2O, S, Tb (<.5 ppm), Yb (<1.5 ppm), Lu (<.8 ppm), Hf (<3.5 ppm), Ta (>.5 ppm), Th (1-4 ppm), Cs (.35-1.5 ppm), Ba (>300 ppm), Rb (>70 ppm) and Cr (5-15 ppm), 25% for Ta (.25-.5 ppm), Th (<1 ppm), U (>.75 ppm), Sr (>250 ppm), Ba (125-300 ppm), Rb (25-70 ppm), Cr (2-5 ppm) and Ni (>200 ppm) and 50% for Ta (<.25 ppm), U (<.75 ppm), Zr (>50 ppm), Sr (<250 ppm), Ba (<125 ppm), Cs (<.35 ppm), Rb (<25 ppm), Cr (<2 ppm) and Ni (80-200 ppm). Unit MV1: (1) WW324, depleted basalt, (2) WW151, enriched basalt, (3) WW132, HREE-depleted dacite flow, (4) WW144A, rhyolite pyroclastic flow, (5) WW275, rhyolite lava flow. Unit FV1: (6) WW277, enriched basalt, (7) WW26, HREE-undepleted dacite tuff, (8, 9) WW414A, WW415, low- and high-silica rhyolite pyroclastic flows, respectively. Unit FV3: (10, 11) WW107A, WW111, low- and high-silica rhyolite pyroclastic flows, respectively.

TABLE 2

CHARACTERISTICS OF VOLUMINOUS RHYOLITIC ASH-FLOW TUFFS FROM SELECTED CENOZOIC TERRANES AND THE MICHIPICOTEN GREENSTONE BELT

Locality	Dominant SiO_2 range	Mean Compositions						Associated volcanic rocks
		Alkalis		$Al_2O_3 + CaO$		FeOt		
		*70-75	>75	70-75	>75	70-75	>75	
Cenozoic, intracontinental rift- or hot spot-related suites								
1. Trans-Pecos Volcanic Province, Texas (n=4 [30,31])	69-75	9.29 (.63)**	---	13.22 (1.25)	---	3.89 (1.12)	---	hawaiite, mugearite, trachyte and comendite lavas
2. Rio Grande Rift, Jemez Mountains, New Mexico (n=9 [32,33])	75-78	---	8.44 (.41)	---	12.72 (.49)	---	.99 (.25)	basaltic andesite to rhyolite lavas
3. Yellowstone Plateau Volcanic Field (n=5 [34])	75-77	---	8.60 (.17)	---	13.20 (.41)	---	1.53 (.25)	olivine tholeiite and rhyolite lavas
Cenozoic, subduction-related, continental intra-arc suites								
1. Oligocene Ash-Flow Sheets, San Juan Volcanic Field, Colorado (n=12 [35])	69-75	8.82 (.99)	---	16.84 (1.09)	---	1.95 (.60)	---	dominant andesite to quartz latite lavas and tuffs, subordinate rhyolite lavas
2. Taupo Volcanic Zone, New Zealand (n=6 [36,37])	69-78	7.23 (.06)	7.74 (.23)	15.27 (.53)	14.07 (.19)	1.80 (.45)	1.23 (.13)	rhyolite lavas, minor high-Al basalt to dacite lavas
3. Mid-Tertiary Upper Volcanic Sequence, Sierra Madre Occidental, Mexico (n=6 [38])	71-75	7.45 (.27)	---	16.09 (.76)	---	1.89 (.26)	---	subordinate high-SiO_2 rhyolite lavas, minor basaltic andesite to dacite lavas
Michipicoten Greenstone Belt								
1. Unit FV1 (n=11)	70-78	6.06 (.82)	5.28 (1.09)	17.15 (.46)	13.92 (.64)	2.53 (.60)	1.63 (.34)	subordinate rhyolite lavas, dacite to rhyodacite tuffs and lavas, minor enriched basalt lavas
2. Unit FV3 (n=8)	70-78	6.44 (2.03)	6.12 (1.00)	17.15 (1.55)	14.32 (1.09)	3.35 (.04)	.93 (.41)	subordinate dacite to rhyolite lavas/tuffs, minor basalt lavas

Compositional data (in wt. percent) are calculated volatile-free.
*Silica interval. n = number of analyses used in the compilation.
**One standard deviation of the mean.

Figure captions

1. Location of the Michipicoten greenstone belt. Areas of detailed geologic mapping are marked by heavy lines and presented in figures 2 and 3. Samples of volcanic rocks that have been analysed for both major and trace elements are located in all three figures.
2. Geologic map of the Michipicoten Harbour area.
3. Geologic map of the Helen Mine-Mildred Lake-Andre Lake area. Key to symbols: (1) conglomerate, (2) breccia unit, (3) shale, siltstone and greywacke, (4) basaltic lava flow, (5) felsic pyroclastic rock, (6) rhyolitic lava flow, (7) felsic intrusive rock, (8) coarse rhyolite breccia associated with Dore sediments, (9) iron formation, (10) mafic and ultramafic intrusive rock.
4. Tectono-stratigraphic correlation diagram for the four geologic sections marked in figure 1. The relative stratigraphic positions of samples located in figures 1, 2 and 3 are indicated.
5. AFM diagram (in wt. percent) for volcanic rock samples (located on figures 1, 2 and 3) from units MV1, FV1 and FV3 of the Michipicoten greenstone belt.
6. Chondrite-normalized [21] rare earth element diagram for the samples listed in Table 1.
7. Location map of the Taupo-Kermadec-Tonga volcanic arc system [26].
8. Minor and trace element concentrations of voluminous continental (A) low-silica (70 - 75 wt.%) and (B) high-silica (>75 wt.%) rhyolitic ash-flow tuffs normalized to chondrites (except Rb, K, P) following the procedure of Thompson et al. [42]. Data sources: low and high-silica Michipicoten rhyolite pyroclastic rocks, units FV1 and FV3 (Table 1), Huckleberry Ridge Tuff and Lava Creek Tuff, Yellowstone

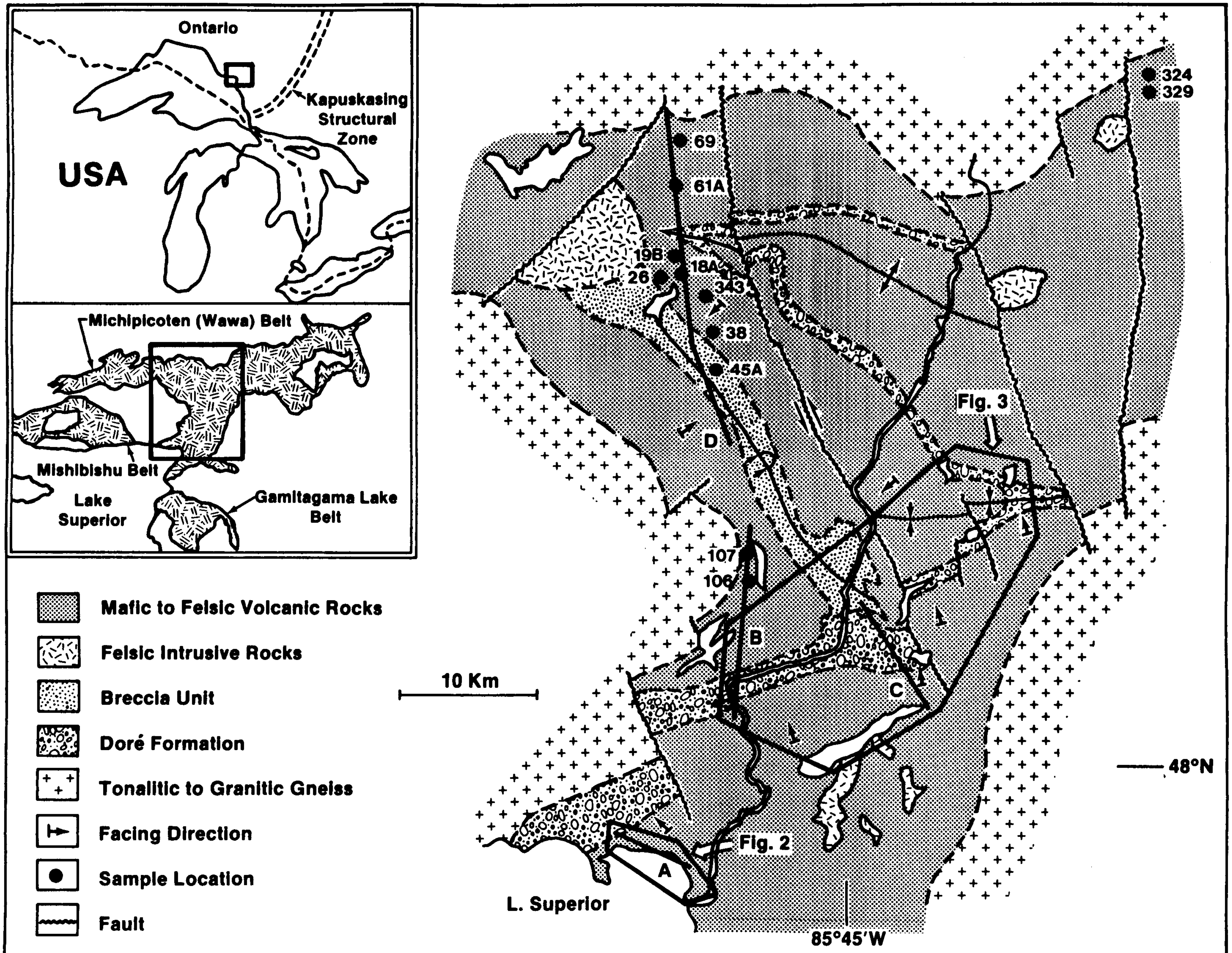
Plateau volcanic field [34], Paisano tuff, Trans-Pecos volcanic province [30], Jemez rhyolite, Rio Grande rift [42], older pumice and Matahina Ignimbrite, Taupo volcanic zone [37, 43-45], typical ignimbrites, Sierra Madre Occidental [38].

9. Normalized [42] minor and trace element compositions of LREE-depleted basalts. Data sources: depleted basalt, unit MV1 of the Michipicoten belt (Table 1), New Britian island-arc tholeiite [40], N-type MORB and the Preshal Mhor basalt from the Isle of Skye [42].

10. Enriched and depleted Michipicoten lower sequence basalts from Table 1 compared on the normalized [42] minor and trace element abundance diagram. Also shown is the basal rhyolite of Michipicoten Harbour (sample WW185, figure 4), which may have been a contaminant involved in the petrogenesis of the enriched basalts.

11. Volumetrically minor high-silica (>75 wt.%) Cenozoic rhyolites from Saipon Island, Mariana frontal arc [48], Garua Harbour, New Britian island arc [47] and the Undu Volcanic Group, Fiji [46] compared to the Andre Lake rhyolite, a thin bed of high-silica rhyolite (sample WW275, Table 1) from unit MV1, Michipicoten greenstone belt. Elements are normalized after Thompson et al. [42].

12. General geology of the Wawa and Abitibi subprovinces and surrounding regions. Subdivision of the Abitibi subprovince from Ludden et al. [53].



Ontario
USA
Kapuskasing
Structural
Zone
Michipicoten (Wawa) Belt
Mishibishu Belt
Lake
Superior
Gamitagama Lake
Belt
Mafic to Felsic Volcanic Rocks
Felsic Intrusive Rocks
Breccia Unit
Doré Formation
Tonalitic to Granitic Gneiss
Facing Direction
Sample Location
Fault
10 Km
324
329
69
61A
19B
18A
26
343
38
45A
D
Fig. 3
107
106
B
C
Fig. 2
A
L. Superior
85°45'W
48°N

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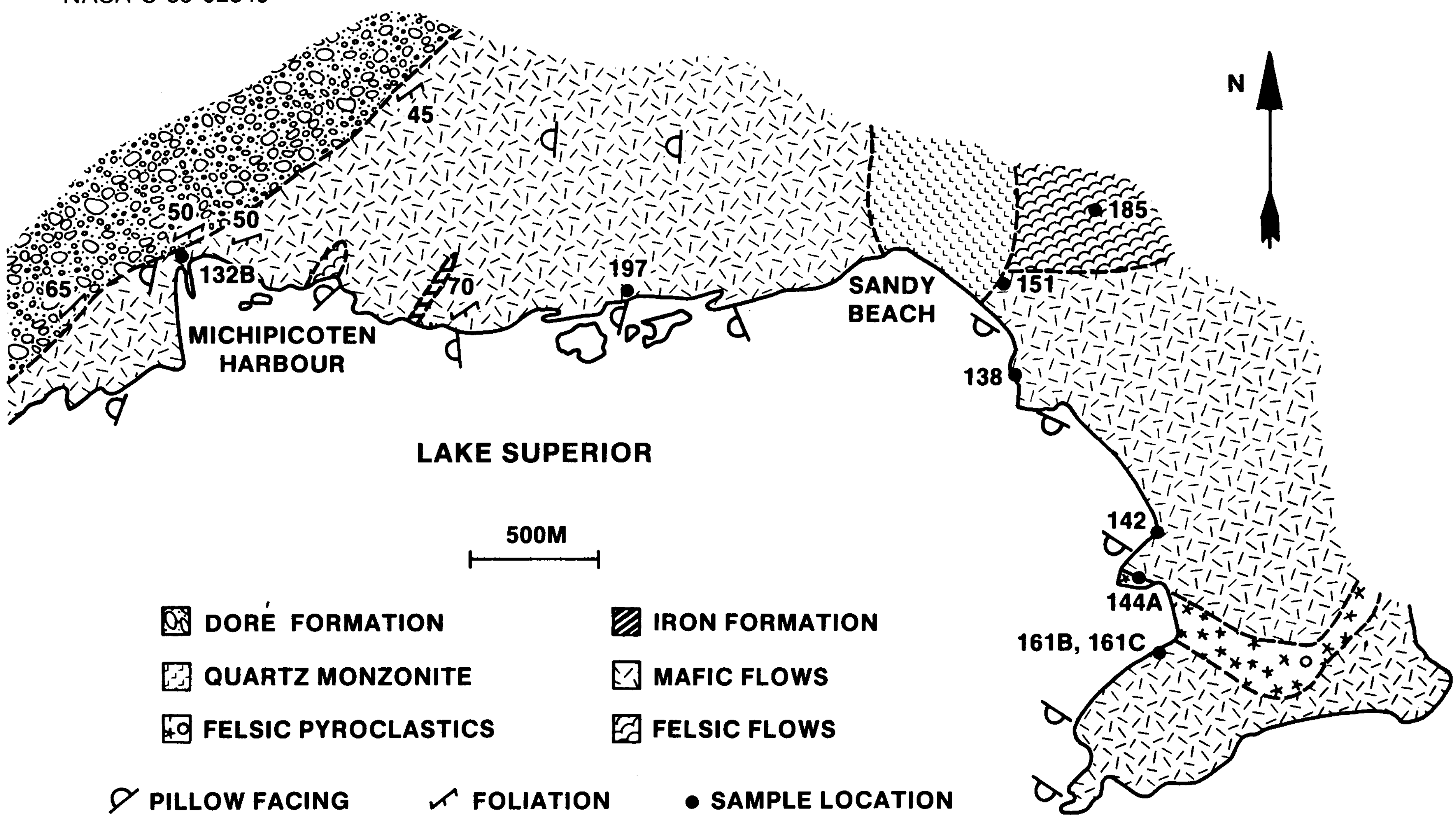

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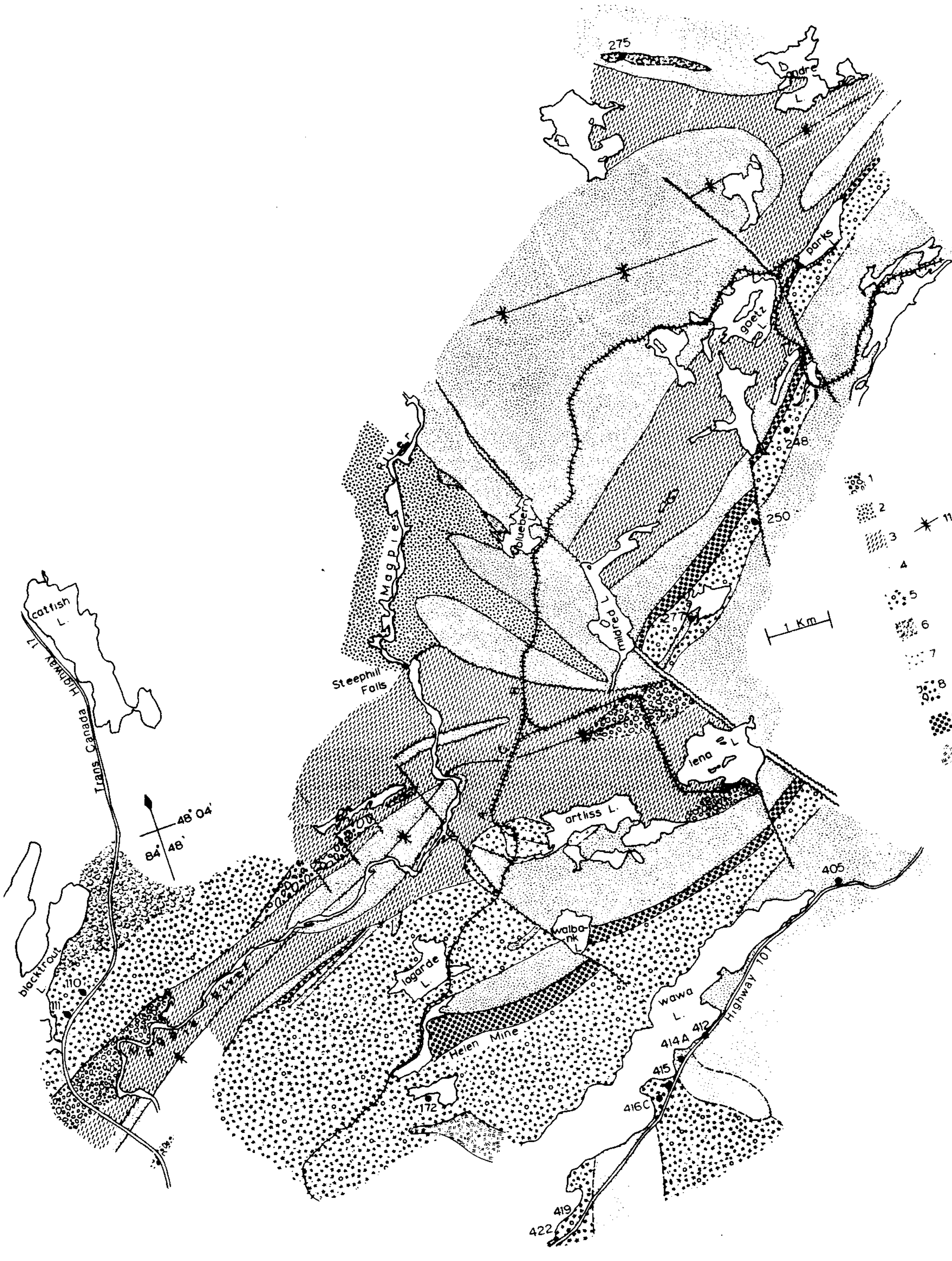

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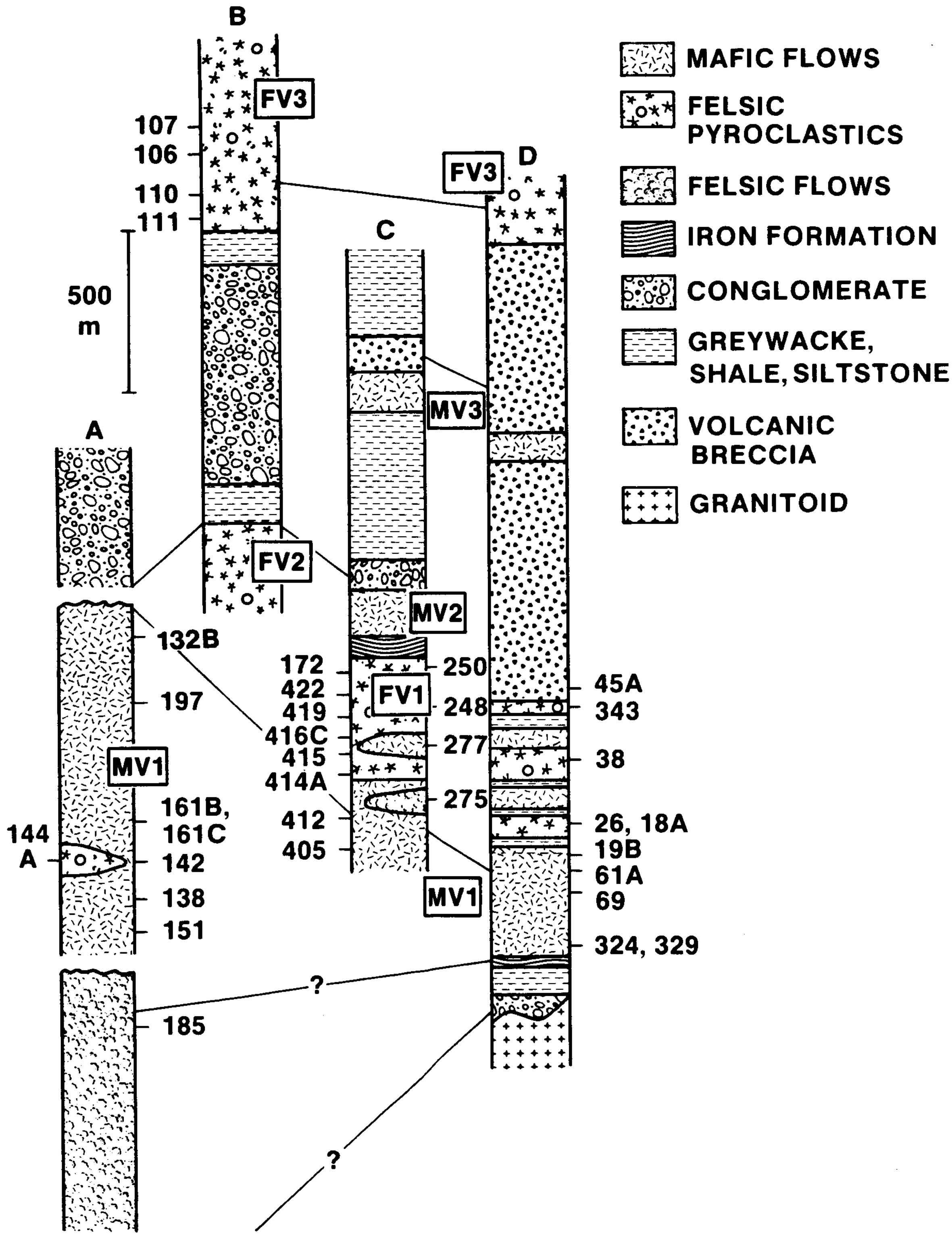

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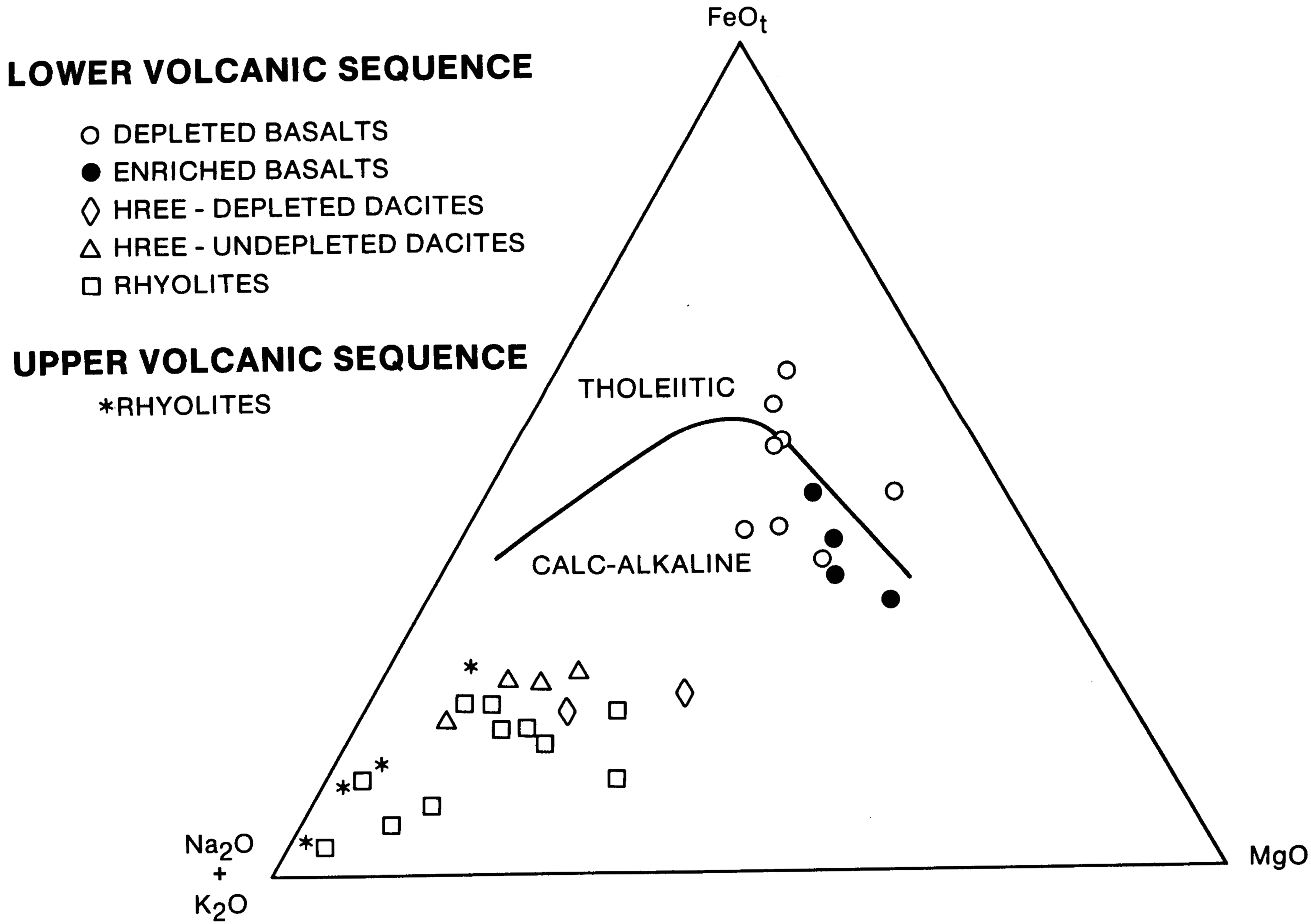

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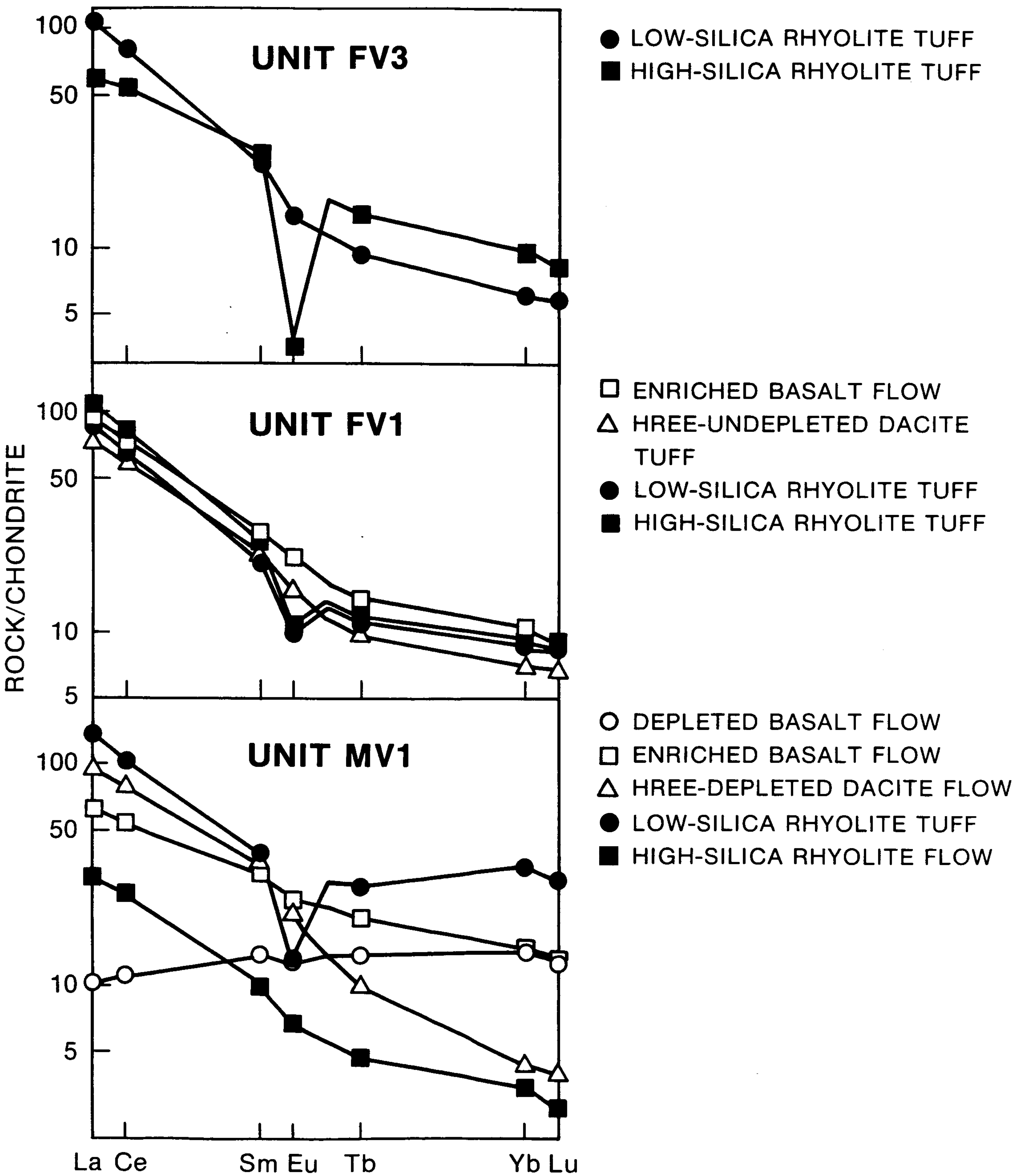

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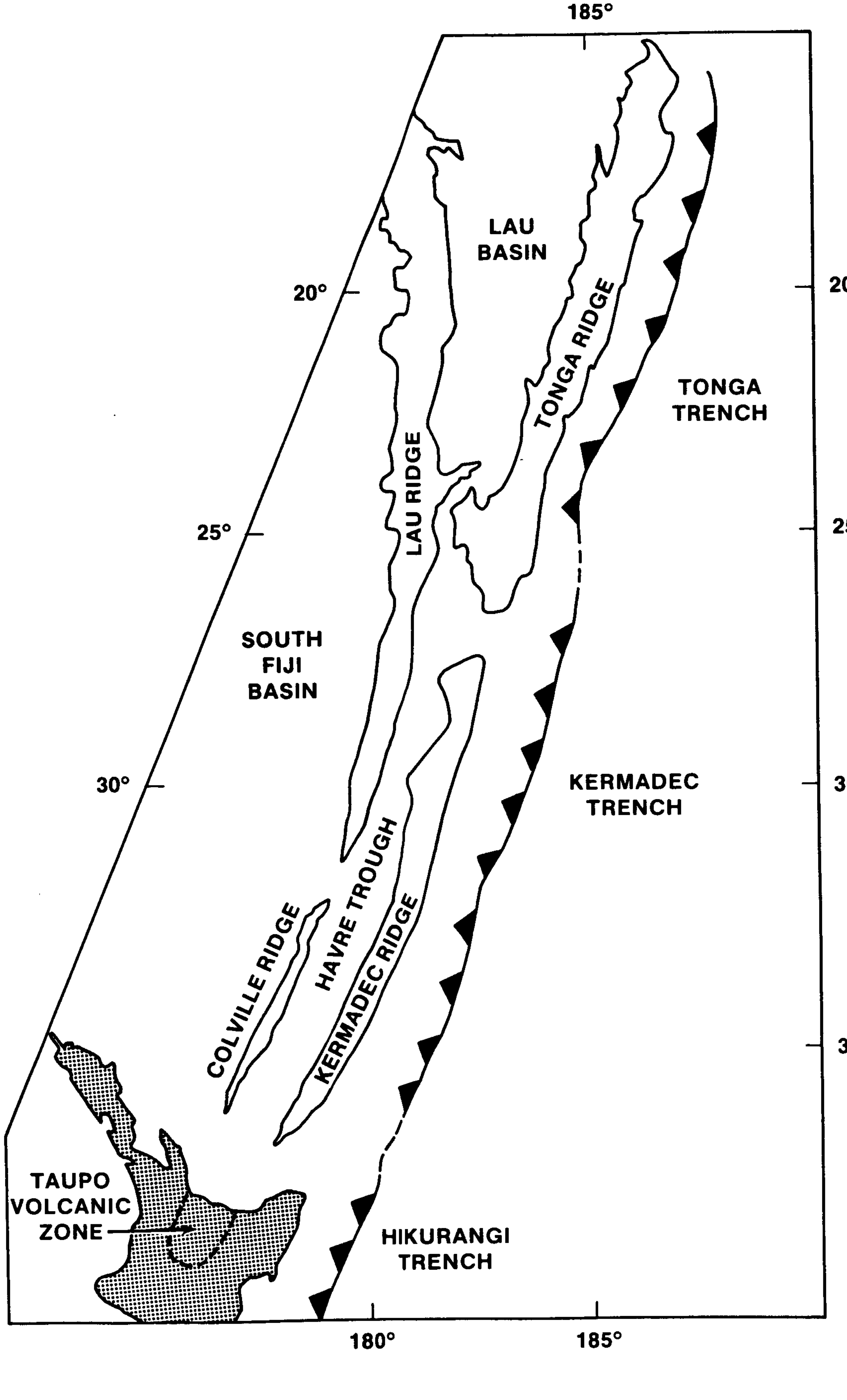
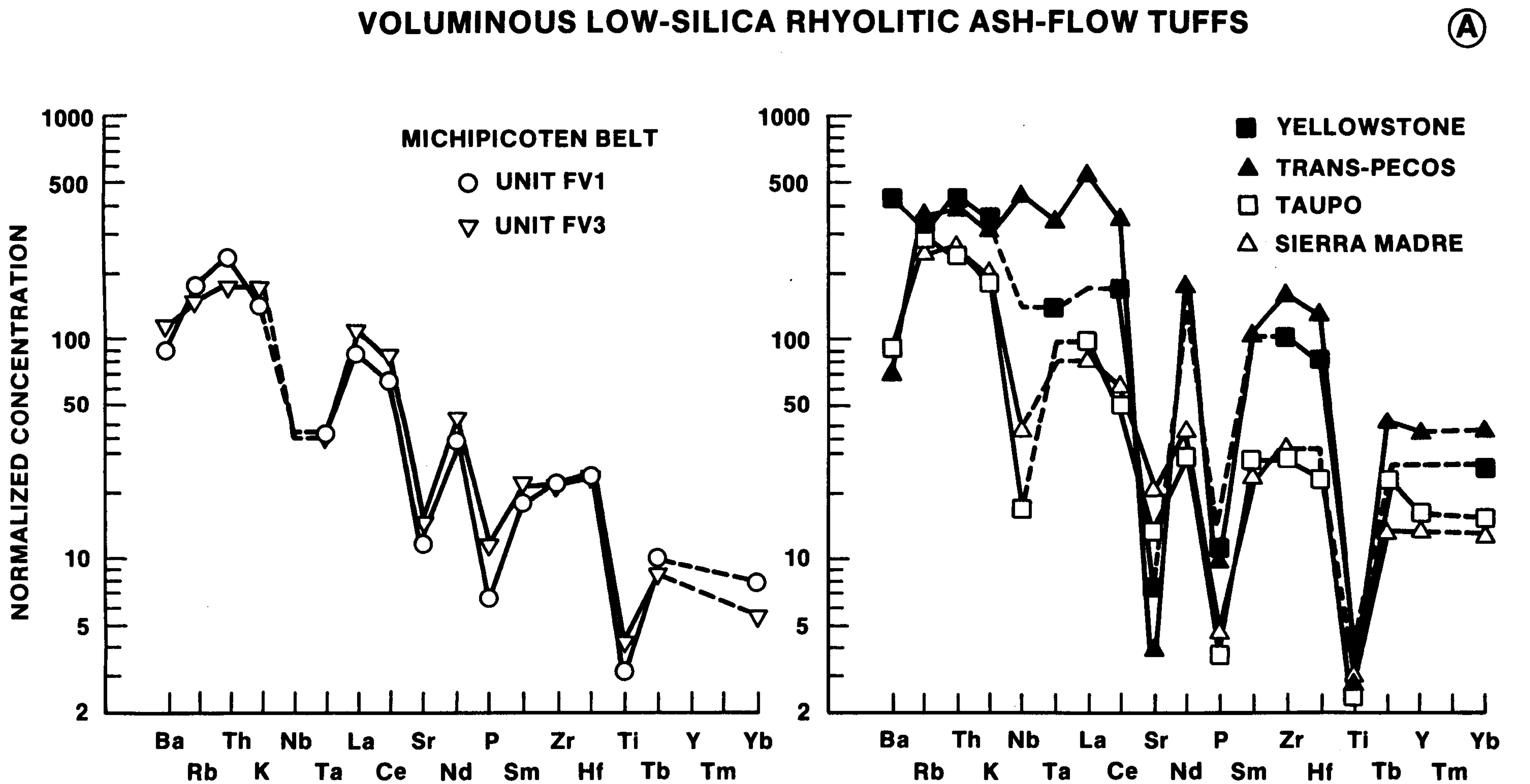
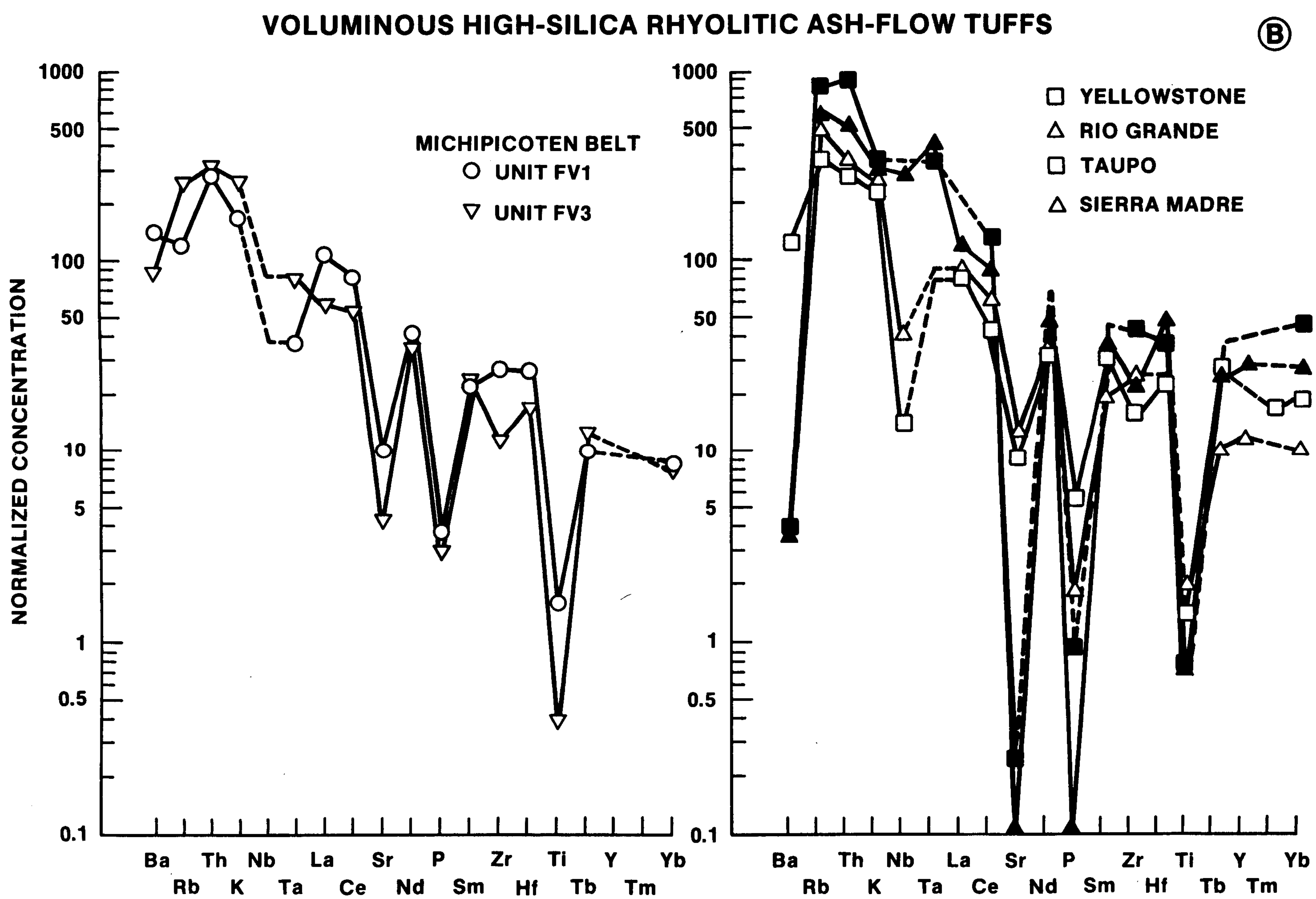
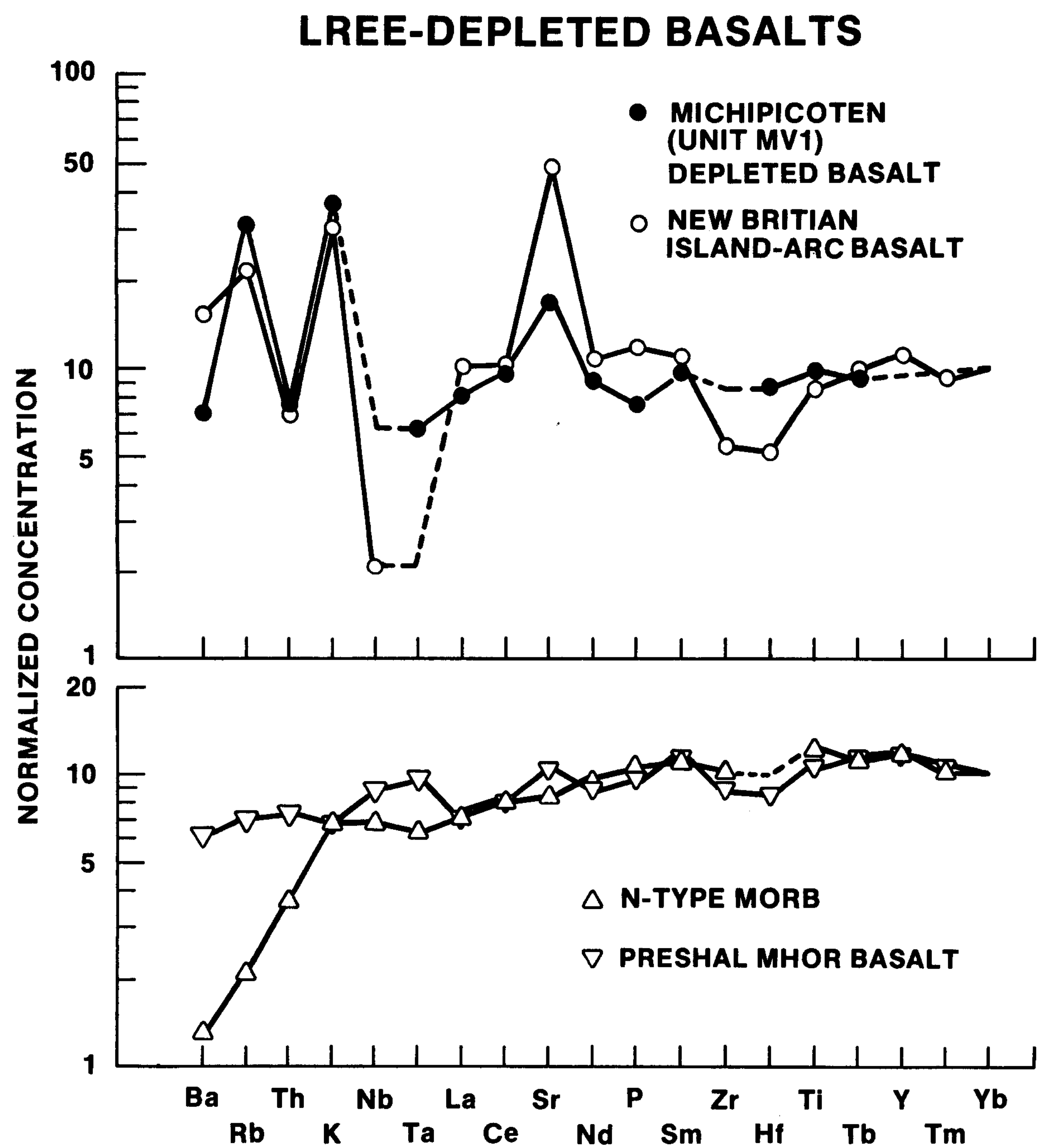


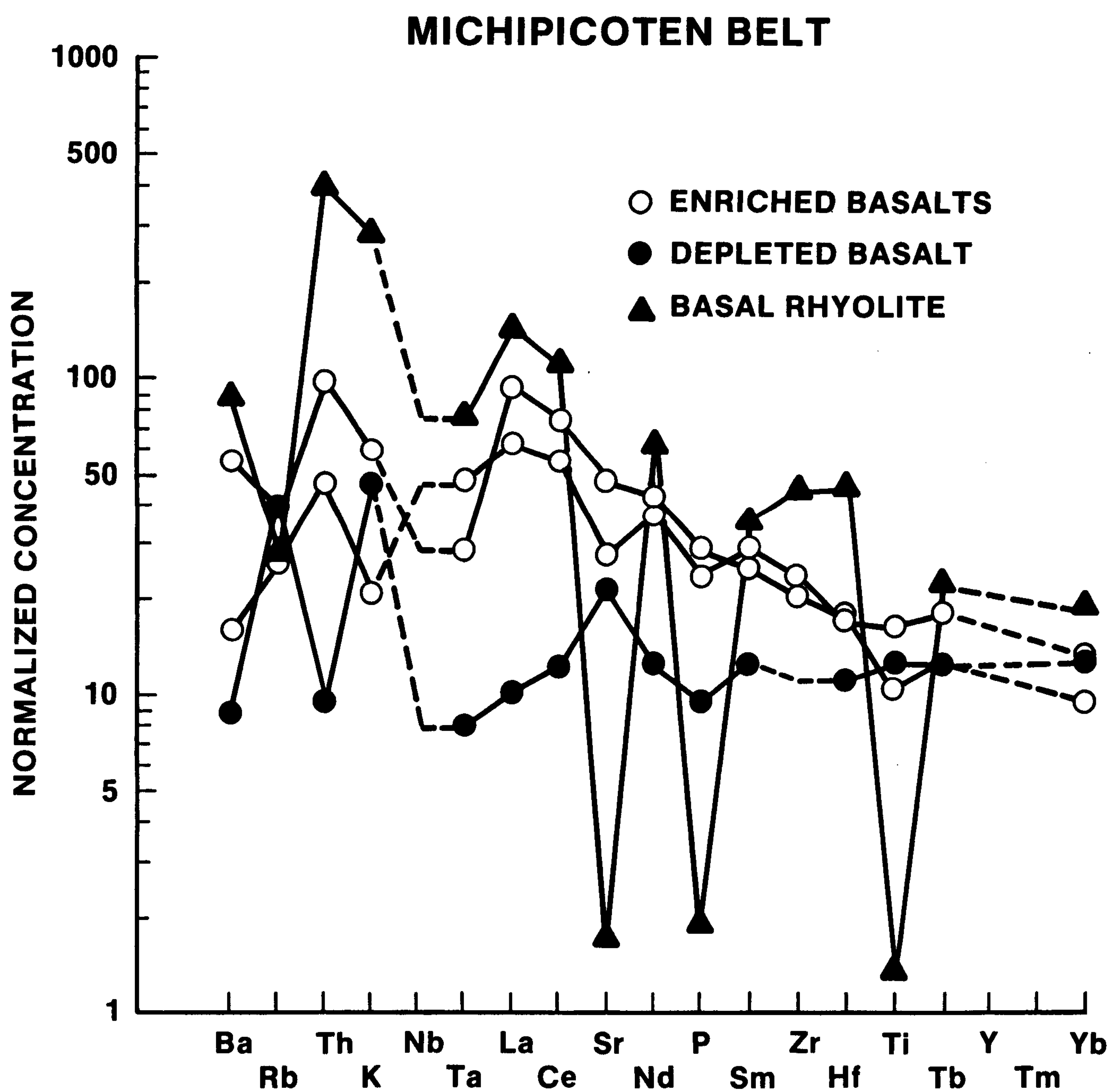


VOLUMINOUS LOW-SILICA RHYOLITIC ASH-FLOW TUFFS
A
NORMALIZED CONCENTRATION
1000
500
100
50
10
5
2
MICHIPICOTEN BELT
UNIT FV1
UNIT FV3
YELLOWSTONE
TRANS-PECOS
TAUPO
SIERRA MADRE
Ba Rb Th K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb

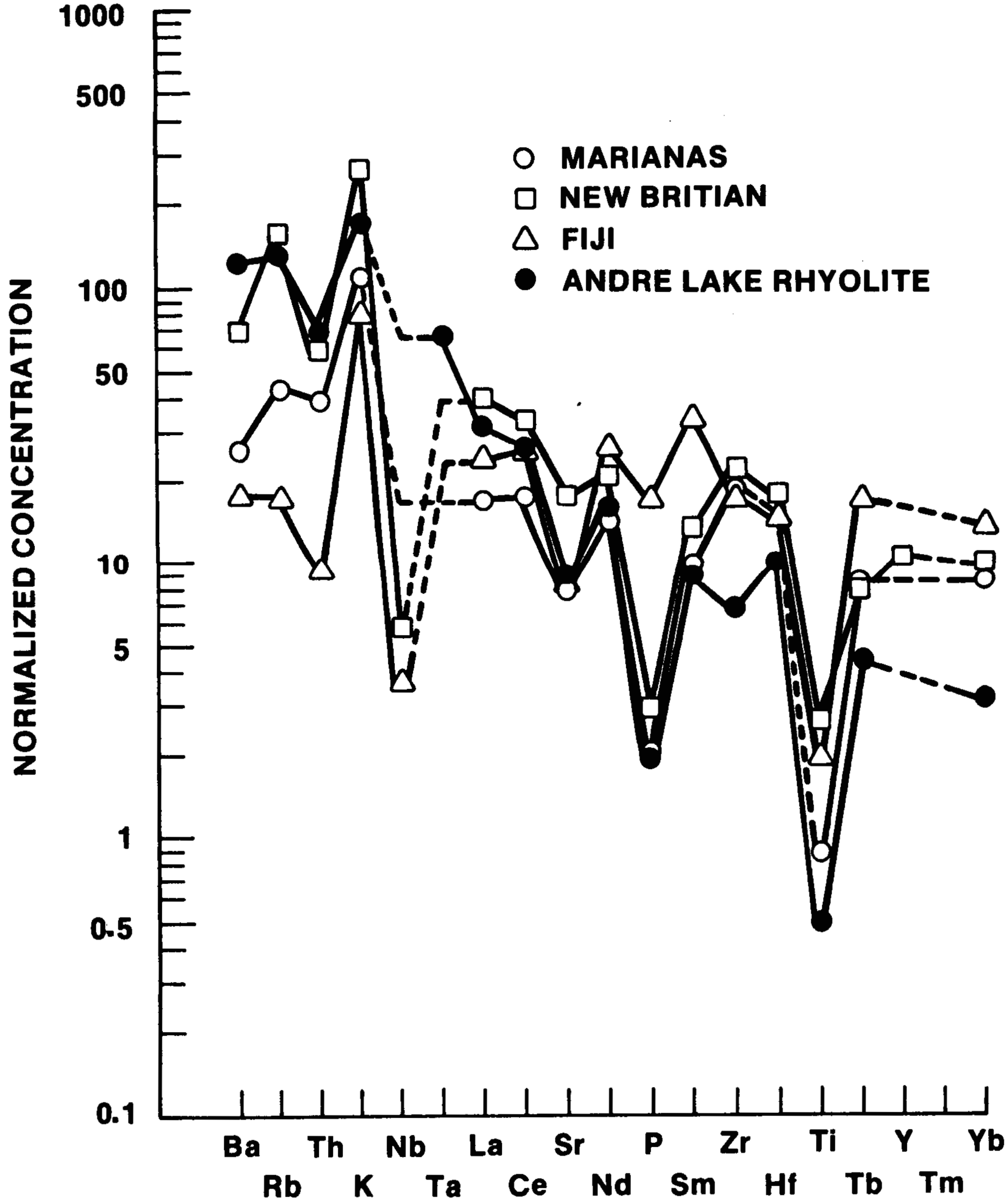


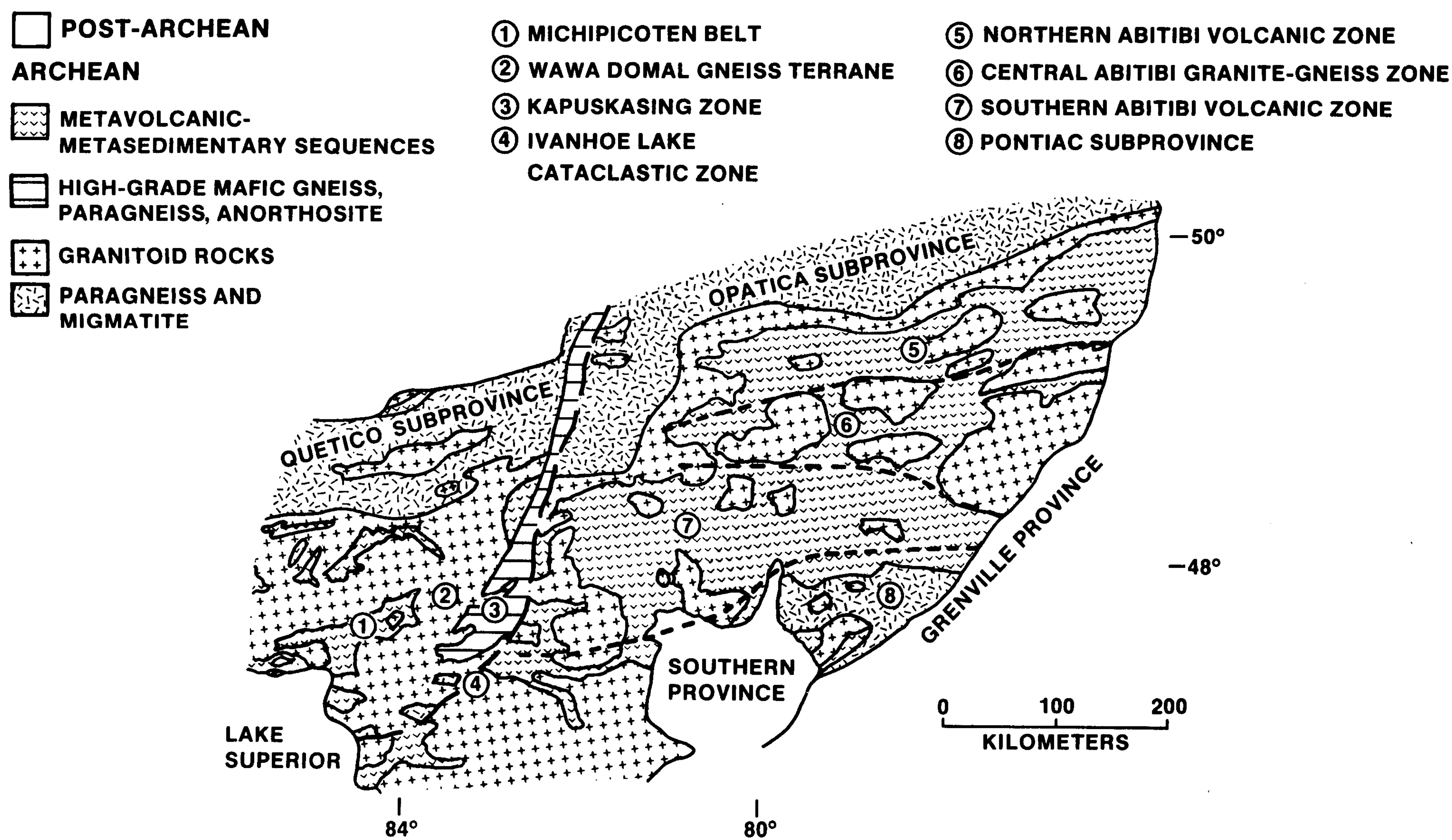
VOLUMINOUS HIGH-SILICA RHYOLITIC ASH-FLOW TUFFS
B
NORMALIZED CONCENTRATION
1000
500
100
50
10
5
1
0.5
0.1
MICHIPICOTEN BELT
UNIT FV1
UNIT FV3
YELLOWSTONE
RIO GRANDE
TAUPO
SIERRA MADRE
Ba Th Nb La Sr P Zr Ti Y Yb
Rb K Ta Ce Nd Sm Hf Tb Tm


LREE-DEPLETED BASALTS
NORMALIZED CONCENTRATION
100
50
10
5
1
20
10
5
1
MICHIPICOTEN (UNIT MV1) DEPLETED BASALT
NEW BRITIAN ISLAND-ARC BASALT
N-TYPE MORB
PRESHAL MHOR BASALT
Ba Rb Th K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb


MICHIPICOTEN BELT
ENRICHED BASALTS
DEPLETED BASALT
BASAL RHYOLITE
NORMALIZED CONCENTRATION
1000
500
100
50
10
5
1
Ba
Rb
Th
K
Nb
Ta
La
Ce
Sr
Nd
P
Sm
Zr
Hf
Ti
Tb
Y
Tm
Yb

HIGH-SILICA ISLAND-ARC RHYOLITES





POST-ARCHEAN
ARCHEAN
METAVOLCANIC-METASEDIMENTARY SEQUENCES
HIGH-GRADE MAFIC GNEISS, PARAGNEISS, ANORTHOSITE
GRANITOID ROCKS
PARAGNEISS AND MIGMATITE
1 MICHIPICOTEN BELT
2 WAWA DOMAL GNEISS TERRANE
3 KAPUSKASING ZONE
4 IVANHOE LAKE CATACLASTIC ZONE
5 NORTHERN ABITIBI VOLCANIC ZONE
6 CENTRAL ABITIBI GRANITE-GNEISS ZONE
7 SOUTHERN ABITIBI VOLCANIC ZONE
8 PONTIAC SUBPROVINCE
OPATICA SUBPROVINCE
QUETICO SUBPROVINCE
GRENVILLE PROVINCE
SOUTHERN PROVINCE
LAKE SUPERIOR
50°
48°
84°
80°
0
100
200
KILOMETERS